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Energy efficiency retrofits in the residential sector – analysing tenants' cost burden in a German field study

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A R T I C L E I N F O

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A B S T R A C T

With the goal of reducing carbon dioxide emissions and curbing climate change, increasing the energy efficiency of buildings with energy efficiency retrofits is an important task. In Germany a large share of the residential building stock is rented. This comes with barriers to energy efficiency retrofitting due to split incentive problems. Alongside existing government incentive programmes, the German tenancy law allows landlords to add a maximum of 11% of the energy-related modernisation costs onto the annual rent. Studies evaluating the actual outcomes, from an energy as well as a social point of view, are rare. This article compares calculated theoretical heating energy consumption for prior to and after retrofit with actual consumption data after retrofit. Further, the issue of household expenses is addressed by comparing increased rental costs after retrofit with household's energy expenses prior and after retrofit. Despite a reduction in energy consumption of 70%, more than half of the households faced increased costs due to higher rents after retrofit. Even when increases in energy prices are taken into account, still one third of the households faced higher costs. For a fairer and more effective distribution of costs and benefits, this article stresses the importance of alternative financing models.

1. Introduction

In order to reduce greenhouse gas emissions in the residential sector, the German government aims to increase the rate of energy efficient renovations to 2% among other measures in the efficiency first initiative (Presse- und Informationsamt der Bundesregierung, 2011). Due to the lack of a clear definition for modernisation rates (Cischinsky and Diefenbach, 2015), the current rate of modernisation ranges from 0.2% with respect to a minimum of four energy refurbishment measures in a building (Rein, 2016) to 0.8% or 1% without further differentiation (Diefenbach et al., 2010; Presse- und Informationsamt der Bundesregierung, 2011). But energy policy also bears economic and social effects. In the case of retrofitting measures, it is stipulated by § 5 Section 1 in the Energy Conservation Act ("Energieeinsparungsgesetz" (EnEG)), that they have to be economically viable and housing should stay affordable. This is especially important, as a large share of the residential building stock is rented out rather than owner-occupied in Germany – but it is the landlords and housing companies who are the decision-makers when it comes to an energetic retrofit.

While efficiency measures are often considered as the method of choice to prevent energy poverty (Boardman, 1991; Brunner et al., 2012), they are also accompanied by problems such as "energetic gentrification" through an upgrade of neighbourhoods and accompanying increased rents, and thus a displacement of residents (Großmann et al., 2014). In Germany it is often claimed that retrofits should be designed "warmmietenneutral", which means that the increased rent is offset or even outweighed by the energy savings (BMWi, 2014). However, empirical assessment of energy efficiency retrofits from the tenants' point of view, which include the actual reduction in heating consumption, is rare (cf. Section 2). This paper aims to contribute to this field by presenting results from a case study of 10 retrofitted buildings from a social housing company in Germany. The study provided a unique occasion to gather data not only on planned energy reductions, but furthermore, actual consumption data of buildings and households over a period of six years. This data made it possible to compare actual consumption and costs of households prior to and after retrofit.

Deviations between the theoretical heating consumption, i.e. the calculated consumption based on standard assumptions, and the measured heating consumption, have been reported in expansive literature: next to faulty retrofit work or misconceptions in regard to the calculations of theoretical consumption, the heating behaviour of a household is also posited as a possible reason for the observed deviations (Calì et al., 2016; Galvin, 2013; Guerra-Santin et al., 2009; Sunikka-

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Blank and Galvin, 2012). Therefore, data on the theoretical consumption of households both before and after a retrofit is assessed in order to analyse the extent to which the heating behaviour influences the consumption, and thus the respective heating costs.

The article is structured as follows. Section 2 introduces the energy efficiency policies in the German building sector and provides an overview of studies that assess the socio-economic impact of energy efficiency retrofitting. In order to take the deviation from the actual heating consumption to the theoretical heating consumption into account, we assess flat[1]-specific theoretical consumption. The respective methodological basis for this is explicated. Section 3 provides information on the data collected and the method used for the analyses of households' theoretical heating energy consumption, their actual individual heating consumption and cost burden prior to/after the retrofit. In Section 4 the empirical results of the case study are presented and analysed. Finally, the article concludes with policy implications in Section 5.

2. Background and literature review

2.1. Energy efficiency policies in the German building sector

Along with policy instruments from Denmark and the UK, the German CO_2 Building Rehabilitation Programme (CO_2-Gebäudesanierungsprogramm) is internationally recognised as a front-runner in the field (Murphy et al., 2012). Based on European guidelines from the European Parliament and Council Directive on the energy performance of Buildings (2010/31/EU), the legal framework in Germany to promote energy transition in the building sector is the Energy Conservation Act (EnEG). It serves to implement Federal Government decisions and also provides the legal basis for the amendment to the Energy Savings Ordinance (EnEV) (Federal Ministry for Economic Affairs and Energy, 2018). § 5 Section 1 in the Energy Conservation Act stipulates that energy efficiency retrofitting has to be economically viable and housing should stay affordable. The federal development bank (Kreditanstalt für Wiederaufbau (KfW)) operates the dominant policy instrument of the economic incentive programme. KfW loans and grants are coordinated with EnEV and are supposed to increase energy efficiency in existing dwellings. Funding is only granted by the KfW if the refurbished building consumes no more than 115% compared to the legal maximum primary energy demand for space and water heating of a new built EnEV reference building. Since the EnEV 2009, energy efficiency retrofitting is obliged to meet the existing mandatory minimum thermal standards for the renovation of existing homes whenever more than 10% of the building is repaired or replaced (e.g. work on the façade or windows) (§ 9 Section 3 EnEV). With regard to a retrofit of existing dwellings the programme comprises five different levels of loans –"KfW Efficiency House" 55, 70, 85, 100, 115 – as well as providing a loan for heritage buildings and loans for individual measures, such as a window replacement. The different levels correspond to the ambitiousness of the refurbishment: KfW Efficiency House 55 represents 55% of the maximum primary energy requirement, 115 represents the minimum standard to obtain funding (KfW, 2017).

Despite the funding programmes, the issue of who bears the costs and who benefits from energy efficiency retrofitting is recurrent. This is crucial in Germany as more than half of the residential buildings are rental units (Statistische Ämter des Bundes und der Länder, 2015). The issue of barriers to finance energy efficiency retrofits in rental units is discussed under keywords such as the agency problem, split incentive problem or principal-agent problem (Bird and Hernández, 2012; Gillingham et al., 2012; März, 2017; Renz and Hacke, 2017; Wood et al., 2012). These keywords refer to the situation in which the person making the investment to increase energy efficiency (landlord) is not the same person who benefits from it by the reduced energy costs (tenant). In order to facilitate and foster energy efficiency retrofitting, the German tenancy law allows landlords to allocate 11% of the modernisation costs onto the annual rent (§ 559 German Civil Code (BGB)). After landlords have allocated the maximum of 11% onto the rent, they are obliged to wait until the local rent level is reached. Once the rent is equal to the local rent index,[2] the landlord has no additional revenues to redeem the retrofit costs. In residential regions where the housing market is not as tense in comparison to many cities in Germany, this can lead to a situation in which landlords have no incentive to carry out costly energetic retrofits at all – as fewer tenants will be willing to pay the high rent in the first place (DENA, 2010).

2.2. Assessing the socio-economic impact of energy efficiency retrofitting

An energy efficiency retrofit can have beneficial effects on the indoor climate and health of all occupants, as indoor temperatures in the summer do not rise as high and the presence of draughts as well as cold surfaces are minimised due to the better insulation. Beyond these per se positive arguments when it comes to energy efficiency retrofitting, the issues of affordability and distribution of costs and benefits laid out in the previous section persist. Within this context the trends in fuel prices need to be taken into consideration. Compared to 1999, the price of heating oil, natural gas, electricity and district heating approximately doubled by the year 2017 (BMWi, 2018). As energy services have the perception of a necessary good (Schulte and Heindl, 2017), this increase puts households with low incomes and/or households living in homes with high heating energy consumption under financial pressure. Consequently, more attention is paid to the issue of fuel poverty. Fuel or energy poverty is associated with income poverty, bad housing conditions, a lack of thermal insulation of dwellings and consecutive problems such as health problems due to cold temperatures in the winter or high temperatures in the summer as well as restricted behaviour due to high energy bills (Dubois and Meier, 2016; Healy and Clinch, 2002; Hills, 2011).[3] Energy efficiency retrofits are often presented as one approach to reduce fuel poverty, as heating consumption, related CO_2 emissions and heating costs are reduced while independence from the effects of price fluctuations increases (Discher et al., 2010; Hills, 2011).

The economic viability of an energy efficiency retrofit is predominately analysed from an investors' point of view – i.e. for the house-owner living in the house, private landlords or housing associations. In this context the net present value (NPV) is the prevailing methodology for a cost-benefit analysis, in which the cost of the retrofit is compared with the long-term savings from the decrease in fuel consumption. Other parameters usually included are the technical life-time of the measures implemented, future maintenance costs, the expected annual energy price development, discount rate and inflation (Galvin and Sunikka-Blank, 2012; Henger and Voigtländer, 2012). The costs of energy-related modernisations vary tremendously and depend on the method of calculation as well as on the extent of measures taken (Henger and Voigtländer, 2012).

In the case of a tenancy, both the tenant and the landlord can benefit from the energy efficiency retrofit: by making the property

[1] The term flat in the context of this paper refers to a self-contained housing unit in an apartment building and is synonymous to the term apartment (American English).

[2] A local rent index („Mietspiegel") provides an orientation on the local rent level in the privately financed housing sector in Germany. The local rent index differentiates between municipalities, year of construction, equipment of dwelling etc. There is no obligation for a community to issue such a local rent index, thus not every community has one.

[3] There is an ongoing discussion about measures of energy poverty, for a detailed analysis see (Heindl and Schuessler, 2015).

attractive in terms of appearance, comfort and low energy costs, the landlord profits from long-term rentability, while the tenant benefits from a decrease in heating energy consumption and lower heating costs (Ferreira and Almeida, 2015). On the downside, increased cold rents for energy efficient buildings can lead to a disproportionate burden for low-income households (Wolff et al., 2017a) and/or to displacement effects (BMWi, 2015; Großmann et al., 2014; von Malottki and Vaché, 2013). Nonetheless, in the case of rented properties it is frequently assumed that tenants profit from energetic retrofits. In the "energy efficiency strategy for buildings" the Federal Ministry for Economic Affairs and Energy states that low-income households would profit from retrofits under the assumption that the costs are offset or even outweighed by the energy savings. A simulation from a macro-perspective shows that energy savings would exceed the increased rent costs (BMWi, 2015). The following overview of studies assessing the costs of energy efficiency retrofits and the decrease in energy costs demonstrates that this is not necessarily the case.

In a study conducted by Enseling and Hinz (2006) rent increases have been calculated as between 0.32€/m^2/month for the lowest up to 2.06€/m^2/month for the highest retrofitting standard. Measured against the rent before the retrofit of 4.2€/m^2/month this represents an increase ranging from 8% to 49%. According to the authors' calculations tenants profited from the energy efficiency retrofitting in all scenarios through the decrease in heating costs (ibid.). This statement however is based on calculations with the NPV method rather than observed changes in households' costs. Galvin and Sunikka-Blank (2012) extended the calculations of Enseling and Hinz (2006) by incorporating a factor for year-on-year fuel price elasticity of − 0.476. It is shown that the perceived payback time is lengthened while the net present value is reduced. Without incorporating the fuel price elasticity, high fuel prices increase the profitability – as these high fuel prices would have resulted in high heating energy costs without a retrofit. What lowers the profitability when the price elasticity of demand is included, is the fact that the high fuel price would have led to a proportional higher reduction in energy consumption when no retrofitting had taken place (Galvin and Sunikka-Blank, 2012). The German Energy Agency furthermore calculated the economic efficiency of energy efficiency retrofits in 2010 and found that the savings in energy costs exceeded the rent increase for a necessary break-even point up to the "KfW Efficiency house 70": it is only in the case of the highest energetic standard – the "KfW Efficiency house 55″ – that costs exceeded the savings. For the "KfW Efficiency house 100" for instance, the calculated savings in energy costs amount to 0.77€/m^2/month, with a rent increase of 0.42€/m^2/month, while for a "KfW Efficiency house 55″, the savings amount to 0.99€/m^2/month with a rent increase of 1.17€/m^2/month. The economic feasibility has been calculated by reference to an energy price of 6.5 cent/kWh – an increase in energy prices would therefore lead to an economic feasibility even for the case of a retrofit to the highest standard (DENA, 2010). However, the results of this study are again based on calculations rather than observed measures. A more recent study released by the Heinrich Böll Foundation[4] finds an average rent increase after an energy efficiency modernisation of 1.55€/m^2/month in the city of Berlin. Compared to an average decrease in heating energy costs of 0.50 €/m^2/month, the authors speak of a "significant imbalance" (Hentschel and Hopfenmüller, 2014:17).

To conclude, high costs of overarching retrofitting might not lead to the appropriate decreases in energy consumption when compared to specific but reasonable measurements at moderate costs. Moreover, the higher the standard, the more unlikely the refinancing becomes, while the rent also increases for the tenant. When including the fuel price elasticity of demand into the calculation, energy efficiency retrofitting becomes more unattractive in financial terms for the buildings' occupant. As Testorf et al. (2010) have further shown, through an analysis of the rent increase in percent subject to the ownership structure, the economic viability depends on the market condition: nearly half of private landlords did not increase the rent after a retrofit in 2010 – partly because a rent increase would have been unenforceable due to market conditions (Testorf et al., 2010).

The reported studies have one thing in common: their assessment of economic viability is based on model simulations and/or aggregate measures for the cost burden of tenants. This article focuses on the tenants' point of view and seeks to fill this gap in the knowledge by taking the actual rent increase after the energy efficiency retrofit as well as the households' consumption and heating costs into account. To further differentiate between behaviour-based differences in heating costs, an approach to integrate a flat-specific theoretical energy consumption is implemented.

2.3. Integrating a flat-specific theoretical energy consumption

Calculations of the expected savings through energy efficiency retrofit according to the calculated theoretical energy consumption form the basis for assessment from both ecological as well as economic viewpoints. According to the EU-Directive 2002/91/EC on energy performance of buildings it is mandatory for each building to have an energy performance rating (EPR), and this has been implemented in German law since the Energieeinsparverordnung EnEV (Energy Saving Ordinance) 2007. The EPR is calculated by including factors such as the heating system, building size, heat loss through outer surface area etc., while the user's behaviour is held constant and based on assumptions rather than actual observations (Guerra-Santin, 2011; Wei et al., 2014). The measured value represents the expected energy consumption a building is supposed to have (Sunikka-Blank and Galvin, 2012). This can lead to a situation where the EPR differs from the actual heating energy consumption, for example when energy savings are lower than predicted. This phenomenon is discussed under the term energy performance gap (Balaras et al., 2016; Calì et al., 2016; Hörner et al., 2016; Khoury et al., 2017; Majcen et al., 2016) and is described as a result of prediction uncertainties. Ramallo-Gonzáles distinguishes between uncertainties with respect to the environment (weather prediction), workmanship and quality of building elements (i.e. thermal bridges or *U*-values) as well as human behaviour (i.e. opening windows, indoor temperature) (Ramallo-Gonzalez, 2013).

In regard to energy efficiency retrofitting, the "direct rebound effect" refers to users consuming more due to lower energy costs after an increase in energy efficiency (Sorrell and Dimitropoulos, 2008). In an estimation of direct rebound effects for different socioeconomic groups in the UK, significantly larger rebound effects have been found for low-income households after cavity wall and loft insulations (Chitnis et al., 2014). As elaborated by Sunikka-Blank and Galvin (2012), the method of calculating the EPR, which does not take the actual consumption before retrofitting into account, could provide another explanation for the deviation between theoretical and actual energy consumption. Within this line of thinking, possible savings are not as high as expected because the calculated energy consumption of buildings prior to retrofitting is higher compared to the actual consumption; users in non-renovated buildings consume less than anticipated, which is referred to as the "prebound effect". For the German context, empirical studies have shown a prebound of 33% on average (Galvin and Sunikka-Blank, 2012). Moreover, a comparison of typical *U*-values for solid walls in the UK with actual values from heat flux measurements has shown a large deviation: the standardised *U*-values in older buildings have shown to be up to twice as high as the true *U*-values, implicating an underestimation of envelope thermal performance.

Building characteristics such as floor area, dwelling type and insulation levels have been found to have large effects on the space

[4] The Heinrich Böll Foundation („Heinrich-Böll-Stiftung") is an independent political foundation affiliated with the German Green Party.

heating consumption, however they are not able to explain the entire variability in energy consumption (Sonderegger, 1978; Steemers and Yun, 2009) and only the insulation levels can be targeted when it comes to an increase in energy efficiency (Huebner et al., 2015). Furthermore, various behavioural and socio-economic variables have shown to be significant determinants of residential heating consumption in a variety of studies (Gram-Hanssen, 2010; Guerra-Santin et al., 2009; Meier and Rehdanz, 2010; Wolff et al., 2017b). The importance of behaviour is demonstrated by the fact that the difference in occupants' heating energy consumption even in identical or similar buildings, varying up to the factor of four, is substantial (Fell and King, 2012; Galvin, 2013; Loga et al., 2011).

In summary, the energy performance gap and the diversity of energy use in dwellings may be influenced both by occupant behaviour and the physical characteristics of building components (Li et al., 2015; Webb, 2017). Despite the well-known influencing factors of heating energy consumption, most of the studies assessing the economic and ecologic effects of energy efficiency retrofits mainly refer to EPR calculations (Clausnitzer et al., 2011; Diefenbach et al., 2016; Guske et al., 2017; Simons et al., 2010). By neglecting the impact of occupant behaviour, technical refurbishment potential studies often overestimate potential energy savings (Galvin and Sunikka-Blank, 2013; Haas et al., 1998; Michelsen and Müller-Michelsen, 2010). By integrating the actual energy consumption before and after the retrofit in the analysis, this paper contributes to this field of research.

3. Data and methods

We had the opportunity to gain access to the necessary data with the support of a housing association in a city of southern Germany. For 10 apartment buildings built between 1931 and 1966, which have been subject to energy efficiency retrofitting, we gathered information on the actual energy consumption for the period of 2010–2015 (refurbishment measures took place between 2012 and 2014, therefore meaning not all buildings were retrofitted at once). The buildings have been retrofitted to a moderate standard, i.e. to the "KfW Efficiency House" standards 85–115 (cf. Section 2.1). Heating consumption prior to and post retrofit has been adjusted by climate correction factors.

Additionally, we were provided with the floor and building plans as well as the EPR calculations for prior and post retrofit from restoration plans. The buildings comprise a total living space of 10,572 m^2 and 172 flats before and 164 flats after the retrofit, as 8 flats have been merged within the retrofitting process. So far EPR's are calculated and issued for buildings only. As our case study is based on apartment buildings with households living in non-identical flats, one has to keep in mind that the theoretical energy consumption of flats depends on their position in a building. For instance, flats in the top floor of a building have a larger surface area, thus they are expected to consume more heating energy than flats in the middle of a building. By integrating the flat-specific theoretical heating consumption and thus taking the building physics into account, it can be ensured that a household with above-average costs before or after a retrofit is not automatically classified as a household with behaviour-based exceptional high heating consumption simply because one lives in a flat with a high theoretical heating consumption – i.e. the top floor. Derived from an EPR calculation method for buildings (Loga et al., 2005), the calculation has been modified to estimate the theoretical heating energy consumption for single flats. The building efficiency standard was raised following the German building typology classifications via direct input of the building age and information on whether, and if so, when, the building has been retrofitted. Information such as the flats' floor space, room height, position in the building (basement, ground floor, middle floor, top floor), the number of rooms and the number of exterior walls from the floor and building plans are likewise included into the model. *U*-values, outer surface area of the flat etc. gathered in this way enabled the calculation of the heat losses and gains of the flat and thus the determination of the theoretical heating energy consumption under standardised conditions.[5,6]

The flat-specific theoretical heating energy consumption in kilowatt hours per square metre (kWh/m^2) before and after retrofit will be denoted *EPRflat_prior* and *EPRflat_after* in the following analyses. With the permission of the households we were also able to assess the actual heating energy consumption according to bills before and after the retrofit (denoted *CONSflat_prior* and *CONSflat_after*). As the retrofit of the buildings took place between 2012 and 2014, the overall time span after retrofit for the single observations differs in length between one and three years. Even though research has shown that occupants sometimes need some time to get accustomed to the new heating system (Heesen and Madlener, 2016), a significant difference in annual post-retrofit consumption values for the buildings retrofitted at various points in time could not be confirmed. The average increase of the energy price for district heating available in these buildings during the observation period amounts to 62%, from 0.08 €/kWh in 2010–0.13 €/kWh in 2015.

Apart from giving us the permission to evaluate the heating consumption according to bills, households were also asked to participate in a semi-structured interview. All households living in the retrofitted buildings were approached with the support of the housing association – culminating in a response rate of 27%. The 47 interviews were conducted in 2014 and 2015. They took place in the apartments of the participating households and lasted between 30 and 90 min. The standardised section consisted of a questionnaire with 33 questions addressing various subjects concerning the retrofitting, e.g. general satisfaction with the process as well as acceptance of new heating technologies and structural changes. Information on socio-demographics, i.e. household size, number of children, household income, highest educational achievement and employment relationship was likewise gathered.

All the buildings belong to a social housing company. As Table 1 shows, the average income and the education in our sample is below the average in Germany. The fact that this sample refers to a population with lower income and education makes it possible to estimate the effects on this group especially affected by increasing fuel prices (cf. Section 2.2). Furthermore, the mean age in the sample is rather high as many retirees took part in the study. This particular composition of residents also implies that the results cannot be generalised to the whole population. The narrative-generating part of the interview aimed at households' heating behaviour in winter time, i.e. the way households ventilate or regulate their indoor room temperature as well as their knowledge about heating energy bills. The analysis of these interviews including households' practices and values influencing their heating consumption has been reported in a previous publication (Wolff et al., 2017b). In that study, the room temperature and the efficiency of ventilation as the main behavioural variables have been identified. Ideas, such as having a cosy home and/or the need to save energy, influence the room temperature.

4. Results

The following Sections deal with the results of the performed case study in three stages. First, the energy efficiency retrofit is assessed in terms of heating energy saved on the building and at the household level. Next, the households' financial burden is analysed by comparing the heating costs before and after the retrofit stepwise without and

[5] Both the EPR calculations and the flat-specific heating demand calculator assume a standard behaviour of households, for instance that all households heat up their flat to an average temperature of 19–20 °C (De Meester et al., 2013; Loga et al., 2005).

[6] For further information on the calculation of the flat-specific theoretical heating consumption see (Weber et al., 2017).

Table 1
Demographics of interviewed households, n = 47.

	Mean	Median	Std. Dev.	Mean Germany
Household size	2.69	2	1.44	2
Age of household head	57	59	16.05	43
Monthly net equivalence income in €	1295	1250	365.40	1958
Years of education household head	11.80	12	2.27	12.65

Notes: For German mean values c.f. household size (Destatis, 2016), age (Statistische Ämter des Bundes und der Länder, 2015), net equivalence income (Destatis, 2017), years of education (Rahlf, 2015).

Table 2
Consumption and energy performance data for buildings.

Building	Ø CONS_prior in kWh/year	EPR_prior in kWh/year	Ø CONS_after in kWh/year	EPR_after in kWh/year	CONS_ reduction	Rebound	Prebound
(1)	210 259	252 429	67 768	79 915	68%	2%	17%
(2)	264 538	239 514	77 029	74 525	71%	− 6%	− 10%
(3)	111 162	148 613	33 458	45 049	70%	− 1%	25%
(4)	189 375	190 000	60 165	74 935	68%	− 23%	0%
(5)	155 454	195 000	50 899	77 649	67%	− 21%	20%
(6)	182 614	195 000	44 192	77 649	76%	− 54%	6%
(7)	160 331	234 000	52 267	63 600	67%	14%	31%
(8)	226 530	333 200	63 881	95 900	72%	− 2%	32%
(9)	294 992	363 000	104 116	63 600	65%	40%	19%
(10)	118 655	110 579	35 757	47 957	70%	− 44%	− 7%

including the allocated rent increase. The third stage combines the analysis of consumption and cost burden by comparing the cost burden to the ratio of actual and theoretical heating consumption – making it possible to determine whether households experience higher costs due to behaviour-based high energy consumption or due to the increased rents.

4.1. Savings in heating energy consumption

Table 2 shows the actual heating energy consumption in kilowatt hours (kWh) prior to and after the retrofit (*CONS_prior* and *CONS_after*), as well as the theoretical energy consumption according to the EPR for before and after (*EPR_prior* and *EPR_after*) the refurbishment respectively for each building. The sixth column ("Reduction in energy consumption") shows the amount of metered heating energy reduced with the refurbishment measures in percent. The measured average reduction of energy consumption amounts to 69%, thus, from an energetic point of view, the energy-related modernisation of these buildings has been successful. Additionally, the prebound effect, i.e. the difference between the EPR and the actual consumption prior retrofit in the last column is not as high as in other studies, where it ranges between 26% and 43% (Sunikka-Blank and Galvin, 2012): in this study it ranges between − 10% and 32% with an average of 13%.

Descriptive statistics of the flats as well as their heating demand and households' heating energy consumption according to bills before and after the refurbishment are presented in Table 3. It should be noted that – on average – the actual consumption is not only lower compared to the theoretical energy consumption before the retrofit ("prebound"), but also after the retrofit. As Table 2 shows, a positive rebound effect[7] only occurred in three buildings.

Table 3
Information on flats, households' living space and energy consumption per square metre subject to analysis.

	Mean	SD	Min	Max
Living space in m^2	61	17	27	97
EPRflat_prior in kWh/m^2/year	156	61	63	296
CONSflat_prior in kWh/m^2/year	141	42	26	307
EPRflat_after in kWh/m^2/year	66	20	35	106
CONSflat_after in kWh/m^2/year	45	23	12	121

4.2. Households' costs before and after energy efficiency retrofitting

In Table 4 the actual rent increase per square metre and year as well as that legally possible according to the retrofit costs is listed. The social housing company owns a rather large number of buildings, which gave them the opportunity to cross-finance the costs of retrofit and therefore to impose a much smaller rent increase than the legally possible 11%. Furthermore, it must be mentioned that it is often difficult to differentiate between maintenance/repair costs and costs solely for energy-related measures, as they are frequently carried out simultaneously. The high retrofit costs reported by the housing association point to such a lack of cost separation. However the actual rent increase implemented by the housing association lies between 6 and 13.20 € per square metre and year. These costs are below even the average of 17.4 € calculated from 16 case studies of energy-related measures in the period 2007–2011 in apartment buildings (Henger and Voigtländer, 2012). It is apparent that only a proportion of the possible rent increase has been realised.

In the following, the achieved energy reduction and the rent increase on the household level are compared in order to assess the financial balance. 109 households without missing values for heating costs, actual consumption and theoretical heating consumption, both before and after retrofit, are included into the analysis. Each households' heating costs prior to and after retrofit are denoted as *COSTprior* and *COSTafter* respectively. In addition, the notation *COSTafter+rent* stands for the sum of heating costs after retrofit including the actual rent increase for each household (cf. Table 4).

COSTprior	*Heating costs of household per year in € before retrofit*
COSTafter	*Heating costs of household per year in € after retrofit*
COSTafter+rent	*Heating costs of household per year in € + rent increase per year in € after retrofit*

Fig. 1 compares the *COSTprior* with the *COSTafter*. In line with the large reduction in the heating consumption at the building level, all households (every dot represents one household) profit from the retrofit in terms of heating energy costs – recognisable immediately as all households lie below the angle bisector.

As already mentioned in Section 2, households receive a rent

[7] Defined as the energy efficiency elasticity of energy services consumption (Galvin and Gubernat, 2016) and calculated with the ratio of CONS_prior and CONS_after as well as EPR_prior and EPR_after from Table 2.

Table 4
Rent increase due to building-specific retrofit costs.

Building	Retrofit costs in €/m²	Legally possible rent increase €/m²/year (11%)	Actual rent increase €/m²/year	Actual rent increase in %/m²/year
(1) (2)	644.86	70.94	10.80	1.67%
(3)	848.31	93.31	10.80	1.27%
(4)	765.48	84.20	6.00	0.78%
(5)	775.45	85.30	6.00	0.77%
(6)	763.08	83.94	6.00	0.79%
(7) (8) (9) (10)	472.86	52.01	13.20	2.79%

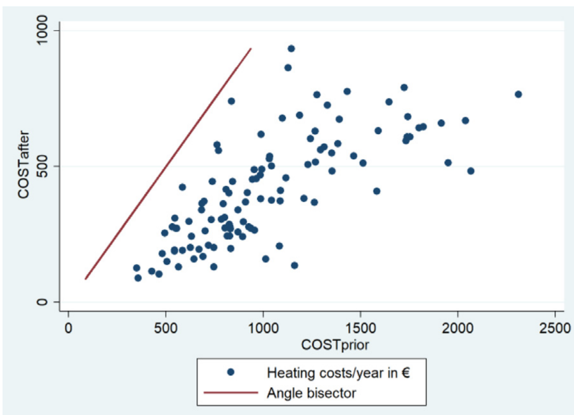

Fig. 1. Comparison of annual heating energy costs prior and after the retrofit at constant energy price.

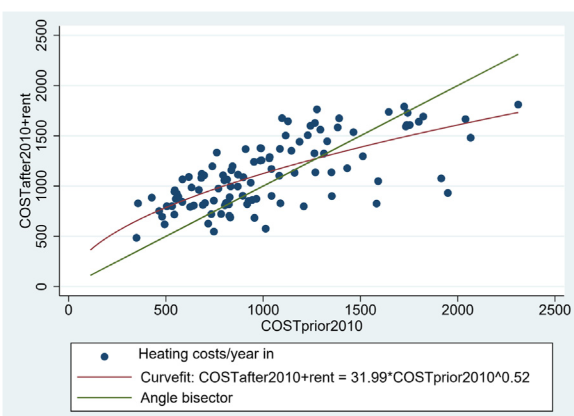

Fig. 2. Annual heating energy costs prior retrofit ($COSTprior_{2010}$) and annual heating energy costs including rent increase after retrofit with base year 2010 ($COSTafter_{2010}+rent$). Curvefit: R-squared: 0.96.

increase as a consequence of the modernisations. Therefore, in Fig. 2 we compare the amount of the heating costs before the retrofit in €/year ($COSTprior_{2010}$) to the amount of heating costs added to the actual rent increase in €/year after the retrofit ($COSTafter_{2010}+rent$) under the assumption of unchanged energy prices (base year 2010) – as this scenario corresponds to the assumption of "warmmietenneutral", i.e. that the increased rent is offset by energy savings.

Starting from the energy price level in 2010, a considerable portion of the households do not profit from the retrofit from a financial point of view. More specifically, more than half (73) of the 109 households lie above the angle bisector in Fig. 2, that is, their cost burden after the energy efficiency retrofit exceeds their prior costs. What is especially noticeable in Fig. 2 is that the cost difference is particularly high for households with low energy costs prior to retrofit: a disproportionally

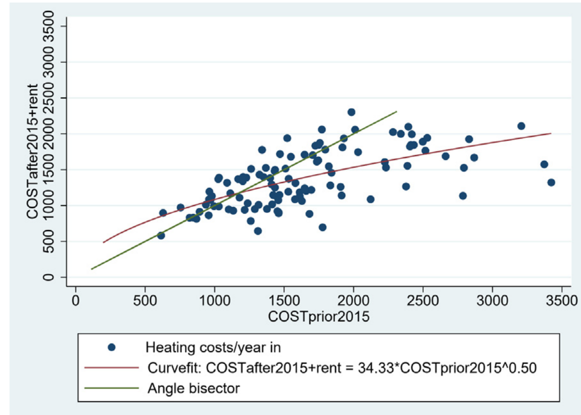

Fig. 3. Annual heating energy costs prior retrofit ($COSTprior_{2015}$) and annual heating energy costs including rent increase after retrofit with base year 2015 ($COSTafter_{2015}+rent$). Curvefit: R-squared: 0.96.

large share of those households with heating costs below 1000 € before the retrofit are above the angle bisector. This finding is also supported by the plotted function (curvefit). It exhibits a power curve with an exponent of 0.52. Thus, the amount of heating costs plus the rent increase after the retrofit increases sublinear with the amount of heating costs before the retrofit.

A common argument in favour of energy efficiency retrofits is that economic viability increases with energy prices. Consumer prices for district heating were comparatively high in the year 2015 (Destatis, 2018). This is why Fig. 3 exhibits the cost burden for tenants in comparing their individual heating costs of the year 2015 plus the rent ($COSTafter_{2015}+rent$) to the heating costs they would have had in 2015 without a retrofit ($COSTprior_{2015}$).

Assuming that households lived in a non-retrofitted building in 2015 with the corresponding energy price level in Fig. 3, only 36 of the 109 households are worse off financially. Again, the plotted function is a power curve with an exponent below one, indicating the sublinear relationship: the higher the heating costs without a retrofit would have been for the tenant, the higher the benefit for tenants from a retrofit turns out to be.

To explore this issue in more depth, the next step will analyse whether and to what extent households have been affected by the rent increase with regard to their individual consumption and the position of their flat respectively.

4.3. Household's financial burden subject to their individual consumption

In order to assess whether households have a frugal or a high consumption in relation to the theoretical energy consumption of their flat, a variable for the ratio of the actual consumption (*CONSflat_after*) and the EPR of the flat (*EPRflat_after*) was constructed (x-axis):

$$ratio\ of\ consumption\ and EPRflat = \frac{CONSflat\_after}{EPRflat\_after}$$

A ratio less than 1 indicates consumption below the EPR of the flat. A ratio above 1 indicates a higher consumption than the EPR. On the y-axis, a ratio of the heating costs prior to retrofit (*COSTprior*) and the heating costs after retrofit including the rent increase (*COSTafter + rent*) has been calculated, in order to assess household's expenses. A ratio less than 1 on the y-axis indicates that the household has lower expenses after retrofit, while a ratio higher than 1 indicates higher expenses after retrofit.

$$ratio\ of\ expenses = \frac{COSTprior}{COSTafter\ +\ rent}$$

Analogously to Figs. 2 and 3, Fig. 4 represents the ratio of expenses

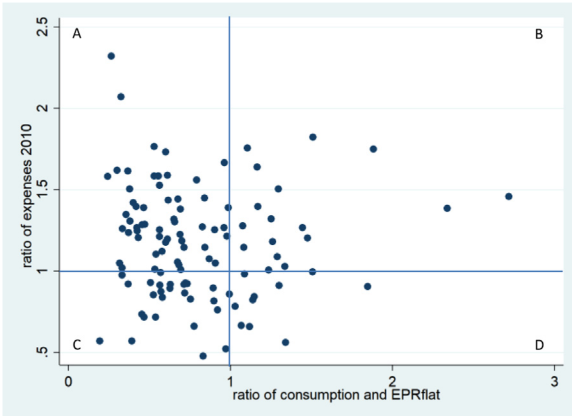

Fig. 4. Comparison of the heating consumption relative to the flat-specific heating demand and the heating costs after the retrofit including a rent increase relative to the heating costs prior retrofit with base year 2010.

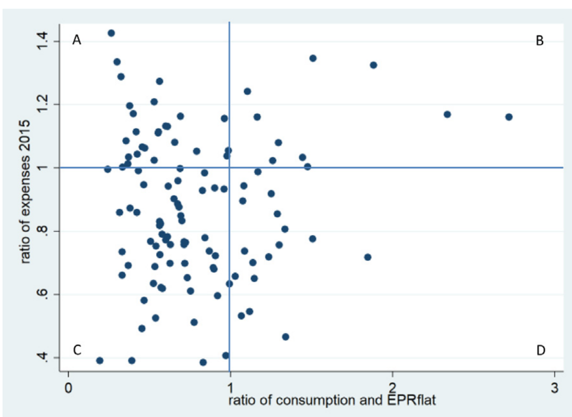

Fig. 5. Comparison of the heating consumption relative to the flat-specific heating demand and the heating costs after the retrofit including a rent increase relative to the heating costs prior retrofit with base year 2015.

with base year 2010, Fig. 5 represents the ratio of expenses with base year 2015.

In Fig. 4 the most interesting field in terms of social justice is field A in the upper left corner of the graph – which incorporates 56 of the 109 households. Due to the increased rent these households are worse off financially (ratio of expenses > 1) while at the same time consuming less heating energy than predicted by the heating demand according to building physics (ratio *CONSflat_after* and *EPRflat_after* < 1). Thus, they economise on heating but spend more in comparison to before the retrofit. Field B in the upper right stands for households (n = 17) that spend more on heating energy and increased cold rent after the retrofit, while consuming more heating energy than the demand predicts for their flat. In this case households are financially worse off, but they also seem to have a preference for higher indoor temperatures and/or do not ventilate efficiently (Wolff et al., 2017b). The 26 households in the bottom left field (C) consume less than the heating demand would predict, thus these households spend less for heating energy plus the increased rent after the retrofit compared to the time before the retrofit. Finally, field D in the bottom right includes 10 households who profit financially from the retrofit as they spend less on heating energy and the increased cold rent, even though they consume more than expected from the building physics perspective for their flat. But compared to field A the number of households facing increased costs after the retrofit, while at the same time consuming less, by far exceeds the number of households profiting.

Partially this result can also be traced back to the power curve functions of Fig. 2 and Fig. 3 and the fact that the amount of heating costs prior retrofit correlates with the position of the households' flat in the building. This shall be exemplified in the following. Household *X* inhabits a flat of 80 m^2 in the middle of the dwelling (building 1, cf. Table 4). With an average heating consumption household *X* paid about 800 € for heating costs in 2010. Household *Y* lives in a flat of 80 m^2 in the same building, but on the top floor. Due to the larger surface area of the uninsulated roof, the heat losses in the winter period are much higher in household *Y* compared to the flat of household *X*. As a result, household *Y* paid 1500 € for heating costs with an average heating consumption in 2010. After the retrofit a rent increase of 9 € per square metre is allocated to both households – leading to an increase of 80 * 9 = 864 €. The allocated rent alone exceeds the heating costs of household *X* before the retrofit. After the retrofit household *X* and household *Y* have heating costs of 300 and 450 € respectively.[8] In sum, the household from the middle of the buildings has higher costs (864 + 300) compared to before, whereas household *Y* in the top floor has lower post-retrofit costs (864 + 450).

When analysing the energy costs with the increased energy price from 2015 in Fig. 5, the overall picture is less negative, however one third of the households still lie above the line for the ratio of expenses (fields A and B), thus facing increased costs. 24% of the households are financially worse off even when energy prices are higher and households consume less than expected (field A). Overall, these results represent a serious flaw in the German retrofit policy. Due to the limited number of cases including information on the heating behaviour (indoor temperature and ventilating behaviour) from the interview (less than n = 30), it was not possible to conduct further inductive analysis regarding a deeper insight on which behavioural aspects influence the outcome of the retrofit from a households' perspective.

5. Conclusion and policy implications

Increasing energy efficiency is an important tool of the energy transition as declared by the German Government. As the results in Section 4.1 show, high reductions in the energy consumption can be achieved even with moderate standards. Hence, claims have been made to promote a higher rate as opposed to higher standards in energy efficiency retrofits (Henger and Voigtländer, 2012). However, the crucial point of our analysis is that despite the very high reductions in energy consumption, for more than half of the households the savings in energy consumption cannot offset the rent increase subsequent to the energy efficiency measures. This result is especially dramatic, because in the case study the allocated costs added onto the rent are below the average compared to other energy-related retrofit costs from reported studies. In consequence, this could lead to households being displaced by the increased costs, an issue which is known as energetic gentrification (Großmann et al., 2014). Research also shows: the higher the retrofit standards become (e.g. the better insulated a house) the higher the influence of the occupants behaviour (De Meester et al., 2013). Due to a limited number of cases including information on the heating behaviour from the interviews, a more detailed analysis of this issue was not possible. Given a higher number of cases, a logistic regression model could give further insight into the effect on the rent increase of single behavioural patterns (i.e. ventilating) while controlling for the building physics' effect.

Nevertheless, the analysis points out that, with the current policy instrument of the 11% rent increase, the aim of a rent neutral energetic retrofit is not very likely to be reached. Above all, it is discriminating households which already have a low consumption, while households with a high consumption are able to profit (irrespective of whether high

[8] The difference in heating consumption/costs between the flats in various parts of the building decreases with an increase in in thermal insulation of the building.

consumption before the retrofit is to be traced back to the position in the building or behaviour). The new German Government targets to restrict the rent increase to 8%. As a result, in addition to future increases in energy prices, the probability that savings might be able to offset the rent increase rises. In the meantime, the split incentive problem persists and there is only little prospect for improvement as long as energetic retrofits remain costly for owners and only some tenants profit from the energetic retrofit with respect to financial aspects. Against this background, claims to adjust current incentive policies as well as adding a climate grant to the housing allowances seem to be more reasonable.

With the goal of increasing energy efficiency retrofits, financing models, such as energy performance contracting, in which the energy efficiency investments are directly repaid by saving in energy costs, are regarded as a possible alternative (Hermann et al., 2015). For the residential sector, on-bill tariffs or pay as you save models seem suitable. They can be designed so that the occupant pays back the cost from the saved amount of the energy/heating bills. The payment can be tied to the heating meter, not the tenant, i.e. in the case of a tenant change the new tenant continues to pay the tariff (Bell et al., 2011). Contracting seems to be particularly reasonable for older buildings with high energy saving potentials. However, they also come along with high transaction costs and uncertainties (Ziehm, 2016). Accordingly, energy performance contracting is slowly becoming more common for municipalities and companies, but it is still unusual when it comes to residential properties (Ástmarsson et al., 2013). Among other things, this can be traced back to the fact that the measurement of energy savings in the residential sector, especially in apartment buildings with multiple residents, is more demanding (Polzin et al., 2016). As this study demonstrated, pre- and post-retrofit energy performance ratings should not be used to calculate energy savings from retrofitting measures, as actual consumption values can differ substantially – both on the building and on the household/flat level. Using actual consumption values would lead to a more realistic estimate of savings, pay back times and cost burdens. In the case of apartment buildings the issue of differing heating energy consumption depending on the position in the building, which also showed to have an influence on the cost burden of tenants after the energy efficiency retrofit in this study, persist. One possible approach to achieve a more equal cost distribution would be the implementation of correction factors for flats with disproportionate theoretical heating energy consumption as it is implemented in the Swiss billing model “VHKA” (Bundesamt für Energie BFE, 1998).

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Declarations of interest

None.

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